

The BBN Manifesto

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In this manifesto I review the current status of standard big bang nucleosynthesis in light of recent observational data and discuss the importance of near-future observations as direct tests of standard BBN.

1. BBN is a Testable Theory

The status of big bang nucleosynthesis (BBN) as a cornerstone of the hot big bang cosmology rests on the agreement between the theoretical predictions and the primordial abundances (as inferred from observational data) of the light elements deuterium (D), helium-3 (^3He), helium-4 (^4He), and lithium-7 (^7Li). The strength of BBN is that it is a testable theory: from its beginnings in the late 1940's, BBN predicted a primordial ^4He abundance of $\sim 25\%$ by mass[1]. Hoyle and Tayler[2] asserted that stars could be found with no ^4He , thereby debunking primordial nucleosynthesis. To the contrary, stars have ^4He at the level of 25% by mass, thus providing the strongest evidence to date that BBN synthesized light elements a few minutes after the big bang. The 1980's saw BBN pass the ^7Li test when the predicted primordial ^7Li abundance at 10^{-10} relative to hydrogen was verified via the observation of lithium in metal-poor halo stars of our Galaxy[3]. The good agreement of standard BBN's predictions with the primordial abundances of the light elements as inferred from observational data allowed us to accurately bound the baryon density of the universe and the expansion rate of the universe at the time of nucleosynthesis[4,5]. As such, BBN provided the critical link for the 'astro-particle connection'. The 1990's have brought a multitude of observations related to the primordial abundances of D, ^3He , ^4He , and ^7Li . In addition to increasing the existing data sets, the recent observations of deuterium in three QSO absorption line systems[6–9] show promise of the first *direct* measurement of a primordial abundance and may provide the next critical test of standard BBN. These improved observations (particularly ^4He) seem to indicate that the concordance between the predictions of standard BBN, simple models for Galactic and stellar chemical evolution, and the observational data may not be as good as we once thought[10,11]. However, because the primordial light element abundances are not necessarily directly measurable, both the quality of the observational data and of the chemical and stellar evolution models used to infer the primordial abundances from this data have become increasingly important as the observational data sets have grown. In

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most cases the observed abundances of the light elements must be corrected for the astrophysical contamination that occurs during the evolution of the Universe and therefore *the determination of the primordial light element abundances is model dependent*. As a consequence, testing BBN theory with inferred primordial observations relies upon models of chemical and stellar evolution that trace the fate of the primordial light elements through various astrophysical environments. With that in mind we discuss below, element by element, the current status of the primordial abundances as they are inferred from observational data. We discuss the relative importance of the extrapolation of the observational data to the primordial abundances: as it stands now, most of the uncertainty in determining the primordial abundances of D and ^3He lies in complex Galactic chemical evolution models whereas most of the uncertainty in determining the primordial abundances of ^4He and ^7Li lies in the understanding of the regions where the observational data is taken (metal-poor extragalactic HII regions and metal-poor Galactic halo stars, respectively). In this manifesto we review the current status of BBN in light of recent observational data and discuss the importance of near-future deuterium observations as direct tests of the standard cosmological model.

2. Predictions

The predictions of the standard BBN are uniquely determined by one parameter, the density of baryons (parameterized by η - the baryon-to-photon ratio), provided we assume a homogeneous and isotropic hot big bang and that the energy density of the Universe at the time of nucleosynthesis (about 1 second after the big bang) is described by the standard model of particle physics ($\rho_{\text{tot}} = \rho_\gamma + \rho_e + N_\nu \rho_\nu$, where ρ_γ , ρ_e , and ρ_ν are the energy density of photons, electrons and positrons, and massless neutrinos (one species), respectively, and N_ν is the equivalent number of massless neutrino species which, in the standard BBN is exactly 3). The current predictions of standard BBN are made with essentially the same code as developed by Wagoner[12] in the early 1970's (for a review of the current status of BBN predictions, see any of the following:[5,13–15]). The changes in BBN on the theoretical side have mostly involved refinements and reductions in the uncertainties in the input physics (*e.g.*, nuclear reaction rates and neutron life-time) to the point where, with the possible exception of ^7Li , the errors in the predictions are much smaller than the uncertainties in the inferred primordial abundances. In Figure 1 we show the predictions of standard BBN (*i.e.*, assuming a homogeneous and isotropic Universe with 3 massless neutrino species) as a function of η [10]. The width of each curve represents the $2 - \sigma$ uncertainty in the predicted abundance. Increasing η corresponds to increasing the nucleon density during nucleosynthesis and therefore increasing the efficiency of nuclear reactions, both in destroying more D and ^3He and in creating more ^4He . ^7Li falls and rises due to a competition between destruction and production reactions.

3. Observations

With the predictions of standard BBN well-understood, we turn to the data for a critical comparison. As mentioned above, the primordial abundances are, with the possible exception of deuterium (see the discussion of QSO absorption line systems, below), obtained from contaminated data and therefore we must rely on a model for the evolution

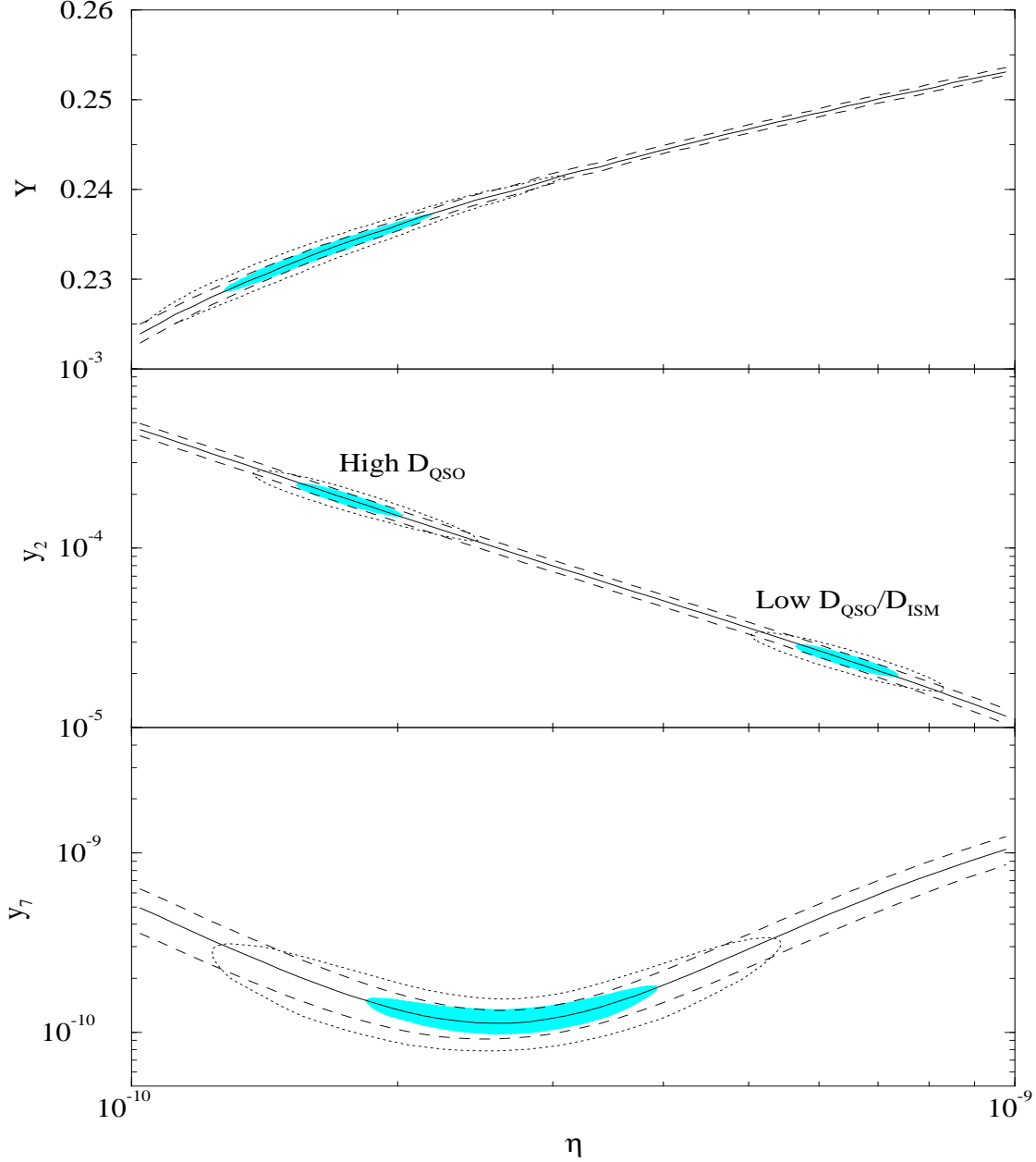


Figure 1. The standard BBN predictions for the abundances of D, ^3He , ^4He , and ^7Li as a function of η , the baryon-to-photon ratio. Dashed curves are the $2-\sigma$ uncertainties in the predicted abundances. Also shown in overlay are the inferred primordial abundances for these light elements and the two possible deuterium abundances from QSO absorption line systems (see text for discussion).

of a given element as it is processed thru one or more generations of stars and as it is enhanced or depleted by galactic processes (*e.g.*, infall of primordial material or outflow of processed material, respectively). Our goal is to derive bounds on the primordial abundances which are as insensitive to the details of their processing history as possible. Below find short reviews of the current status of each of the BBN elements.

3.1. Helium-4

Compared to D, ^3He , and ^7Li , the evolution of ^4He is the simplest to follow. Stars produce ^4He as a by-product of hydrogen burning and massive stars produce metals (Carbon, Nitrogen, and Oxygen). Therefore we expect the amount of ^4He in a star and the abundances of CNO nuclei to be correlated[16]. Using the ^4He abundances from more than 60 metal-poor extragalactic HII regions[17–19], Olive and Steigman[20] find from a least-squares regression:

$$Y_p = 0.234 \pm 0.002 (\text{stat}) \pm \Delta Y_{\text{syst}}, \quad (1)$$

where ΔY_{syst} represents any residual systematic errors in the derived ^4He mass fractions. Other than the correlation of stellar production of ^4He with CNO production, there is no chemical evolution dependence to this result. Note that this analysis includes the entire Izotov *et al.* [19] data set of 27 HII regions and has the same $2 - \sigma$ upper-limit to Y_p as previous estimates[21]. Also note that a simple average the lowest metallicity HII regions yields an identical $2 - \sigma$ upper-bound to Y_p [20]. The real issue here is the size of the systematic errors which accompany the conversion of the intensities of singly ionized ^4He emission lines to total mass fractions of ^4He . In the following discussions, I'll assume $\Delta Y_{\text{syst}} \sim 0.005$, the level independently estimated by several groups[17,18,21,22], and return to the possibility that it may be required to be larger[14].

3.2. Lithium-7

Next we turn to lithium. ^7Li is made in the big-bang at levels greater than $\sim 10^{-10}$ relative to hydrogen. Its abundance, as observed in about 100 metal-poor ($-3.8 \leq [\text{Fe}/\text{H}] \leq -1.3$) halo stars[23–25] is roughly constant with respect to metallicity (and for $T_{\text{eff}} \geq 5800\text{K}$):

$$\left(\frac{\text{Li}}{\text{H}}\right)_{\text{Halo}} = (1.6 \pm 0.1) \times 10^{-10}. \quad (2)$$

The constancy of this plateau as a function of metallicity and stellar surface temperature is taken as evidence that the Pop. II halo star lithium abundance is in fact very close to the initial lithium abundance of the gas which formed these stars. In order to interpret this as the primordial lithium abundance we must ensure that substantial depletion or creation of lithium-7 could not have occurred. The halo stars may have started with a higher abundance of lithium and then uniformly depleted lithium down to the observed plateau abundance[26]. Observations of ^6Li , Be, and B in these same stars limit the amount of such depletion to be no more than a factor of two[27,28] and in fact the models of Vauclair and Charbonnel[29] that include microscopic diffusion and a modest stellar wind can account for all of the correlations and dispersions claimed to exist in the plateau provided the initial abundance of ^7Li is no greater than $\sim 3 \times 10^{-10}$ relative to hydrogen. On the other hand,

some of the lithium contained in halo stars may have been made by cosmic ray spallation in the gas prior to their formation. Again, observations of Be and B in these stars limits the spallation contribution to be less than 20% of the halo abundance[30]. In addition to the above mentioned systematic uncertainties, there are systematic uncertainties associated with the modeling of the stellar atmospheres (estimated at $^{+0.4}_{-0.3}$ dex) And so, we estimate the primordial ${}^7\text{Li}$ abundance to be in the range

$$\left(\frac{\text{Li}}{\text{H}}\right)_p = (1.6 \pm 0.1^{+0.4+1.6}_{-0.3-0.3}) \times 10^{-10}. \quad (3)$$

3.3. Deuterium and Helium-3

The lower-bound to primordial Deuterium provides the cleanest constraint on BBN. Since D is destroyed in all astrophysical environments[31], any measurement of deuterium places a chemical evolution-independent lower bound to the primordial abundance of deuterium (and thru the BBN predictions, an upper bound to η). *Whatever the primordial abundances of ${}^3\text{He}$, ${}^4\text{He}$, and ${}^7\text{Li}$, they must be in agreement with this lower bound to deuterium if standard BBN is to be correct.* Two classes of local deuterium observations exist: the pre-solar nebula abundance $((\text{D}/\text{H})_\odot)$ and the abundance in the local interstellar medium (ISM) $((\text{D}/\text{H})_{\text{ISM}})$. The pre-solar abundance of deuterium as inferred from ${}^3\text{He}$ measurements in meteorites and the solar wind[32] is[33]

$$(\text{D}/\text{H})_\odot = (2.6 \pm 0.9) \times 10^{-5}. \quad (4)$$

The ISM deuterium abundance is measured with HST as absorption along the line of sight to relatively nearby stars[34]:

$$(\text{D}/\text{H})_{\text{ISM}} = (1.6 \pm 0.2) \times 10^{-5}. \quad (5)$$

And so, simply using the Universe's inability to synthesize deuterium anywhere but the Big Bang, we have a model independent lower bound to the primordial deuterium abundance:

$$(\text{D}/\text{H})_p \geq 1.2 \times 10^{-5}, \quad (6)$$

which corresponds to $\eta \leq 8 \times 10^{-10}$ and is in good agreement with the inferred primordial abundances of ${}^4\text{He}$ and ${}^7\text{Li}$ reported here.

Although the lower-bound to primordial deuterium is the least model dependent, bounding primordial deuterium from above is a different story since it necessarily involves a model for chemical evolution. Any gas that is processed thru stars has all of its deuterium destroyed. In addition to providing a deuterium destruction factor, models of chemical evolution should also describe observed properties of the Galaxy such as the age-metallicity relation, the gas fraction, the overall metallicity, individual abundance ratios, the lack of metal-poor G-dwarfs in the solar neighborhood, and the ${}^3\text{He}$ abundance at in the pre-solar nebula and in the ISM, to name but a few. At present, the severity of these constraints as well as various models abilities to fit them are in the eye of the beholder. Essentially all models that were constructed prior to the need for large deuterium destruction got a factor of ~ 2 destruction of deuterium. Models of Steigman and Tosi[33] and of Fields[35] are consistent with deuterium destruction by a factor of 2-4 while the

recent models of Scully *et al.* [36] can deplete deuterium by a factor of ten. The difference between the two approaches can be traced to outflow - large deuterium destruction is leveraged against the over-production of metals because massive stars can quickly cycle thru gas (thereby destroying deuterium) but only at the expense of metal production. This leverage can be decreased by expelling the metals from the Galaxy, as highlighted by the stochastic parameterization of Copi *et al.* [37] and explicitly demonstrated in the Scully *et al.* models[36]. It is not clear whether such ‘outflow models’ have anything to do with our galaxy or whether they are better fits to the data than closed models. Perhaps BBN is showing us the way of the future for chemical evolution models?

The evolution of ^3He is more complicated than that of D. Not only do we face similar uncertainties shared by D/H stemming from galactic chemical evolution, but there are considerable uncertainties in the stellar yields of ^3He , particularly in low mass stars. No one gets the correct answer - ^3He is grossly overproduced by the solar epoch in all standard chemical evolution models[38] and even in cases where the primordial abundances of D and ^3He are set to zero, an over-production of ^3He is found [39]. In fact, even in the rather extreme models invoking both stellar and galactic winds, ^3He is always overproduced[40]. We are forced to conclude that the ^3He problem cannot simply be solved by chemical evolution alone and that there must be something wrong with the stellar production and/or destruction of ^3He . It has been argued that an extra mixing mechanism due to diffusion below the convective envelope can lead to the destruction of ^3He in low mass stars while potentially explaining the high ^{13}C abundance in globular cluster red giants[41]. It may be possible that some set of these non-standard models in which some or all of the newly synthesized ^3He is destroyed in low mass stars can simultaneously give the correct ^3He chemolution (*i.e.*, start with a primordial ^3He which is not too large and still account for the pre-solar and ISM ^3He abundances) *and* account for the stellar ^3He production as observed in the PNe *and* explain the ^{13}C anomalies. In that case the maximum amount of primordial ^3He allowed could give a lower-bound to the baryon density which is consistent with that derived from D evolution. Until the problem of ^3He production and/or destruction in low mass stars is resolved, it is difficult to see how ^3He can be used as a probe of BBN.

There is a way to remove the question of the chemical evolution from the picture and that is to measure the abundance of deuterium in sufficiently un-evolved extra-Galactic systems. Such abundances have been measured in high-redshift clouds along the line-of-sight to two high-redshift QSOs. The deuterium in these Lyman-limit absorption line systems appears as blue-shifted (82 km/s) H-like absorption and has the potential of being primordial. Unfortunately there are currently two different deuterium abundances reported and they are separated by an order of magnitude. One group measures along the line-of-sight to QSO 0014+8818[6,7] and reports $\text{D}/\text{H} \sim 2 \times 10^{-4}$. Another group[8,9] has deuterium abundances along two different lines-of-sight (QSO 1937-1009 and QSO 1009+2956) with an abundance roughly 10 times smaller: $\text{D}/\text{H} \sim 2 \times 10^{-5}$. At the time of this talk, there is no way to determine which group, if either, is measuring the primordial deuterium abundance, but something is drastically wrong with either BBN and/or chemical evolution if either of them is.

4. BBN Scorecard

So, how does BBN stack up? The QSO deuterium dichotomy, frustrating in its inability to hone in on the primordial deuterium abundance, proves useful to examine BBN's performance. Figure 1 shows the predictions of standard BBN with the inferred primordial abundances as discussed above in overlay (the dotted contour corresponds to the $2 - \sigma$ range and the shaded region the $1 - \sigma$ range). Also shown are the two QSO deuterium observations. If the low-D QSO abundance is taken to be the primordial deuterium abundance (which is consistent with vanilla chemical evolution models which predict a factor of 2-4 deuterium depletion), there are problems for BBN if the primordial abundances of ^4He and ^7Li are as reported above. The predicted mass fraction of ^4He consistent with this low-D abundance is ~ 0.015 too large and therefore would require a systematic increase in the mass fractions of ^4He as extracted from the observations. This is the 'crisis' as identified by Hata *et al.* [10]. In addition, the ^7Li abundance consistent with low-D is a factor of 5 greater than the plateau value and would require larger-than-anticipated lithium depletion[43,44]. Alternatively, the high-D QSO abundance is perfectly acceptable as the primordial deuterium abundance from the point of view of the abundances of ^4He and ^7Li as reported above[42]. But, it is a nightmare for chemical evolution. This is just another manifestation of the 'crisis' - namely, the primordial abundance of deuterium required by the inferred primordial abundances of ^4He and ^7Li is a factor of ten larger than that implied by standard chemical evolution arguments starting from the ISM deuterium abundance and working backwards[10].

The resolution of this tension lies with better data and the further removed from chemical evolution, the better. It is convenient to look towards the QSO absorption line systems but *caveat emptor*: it is very difficult to find absorption line systems where nearly primordial D can be measured. They must be at high enough redshift to shift the Lyman series into the optical, have high HI column densities, and be 'clean' at 82 km/s (*i.e.*, the cloud itself must be quiet (low temperature and little bulk motion) and the chance of HI interlopers must be small). The state of the art in the QSO game will be in getting high signal-to-noise data so that many lines of the Lyman series can be used to accurately establish the density of HI.

Stay tuned ...

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